

Multiplicity distributions and long range rapidity correlations

T. Lappi

University of Jyväskylä, Finland

Saturation, CGC and Glasma workshop
BNL, May 2010

Outline

- ▶ Multigluon correlations in the Glasma
- ▶ Gluon multiplicity distribution \Rightarrow neg. bin., glitter
- ▶ Forward-backward multiplicity correlations in STAR

Based on:

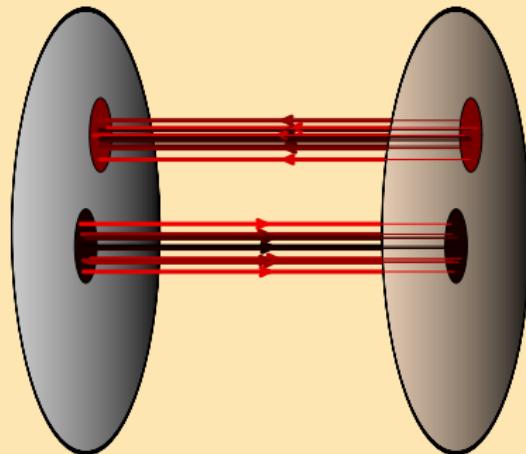
- ▶ F. Gelis, T. L., L. McLerran, "Glittering Glasma," Nucl. Phys. **A828** (2009) 149-160. [arXiv:0905.3234 [hep-ph]].
- ▶ T. L., L. McLerran, "Long range rapidity correlations as seen in the STAR experiment," Nucl. Phys. **A832** (2010) 330-345. [arXiv:0909.0428 [hep-ph]].

Also:

- ▶ F. Gelis, T. L. and R. Venugopalan, *Phys. Rev.* **D79** (2008) 094017, [arXiv:0810.4829 [hep-ph]].
- ▶ K. Dusling, F. Gelis, T. L. and R. Venugopalan, Nucl. Phys. A **836** (2010) 159 [arXiv:0911.2720 [hep-ph]].
- ▶ T. L., S. Srednyak and R. Venugopalan, *JHEP* **01** (2010) 066, [arXiv:0911.2068 [hep-ph]].

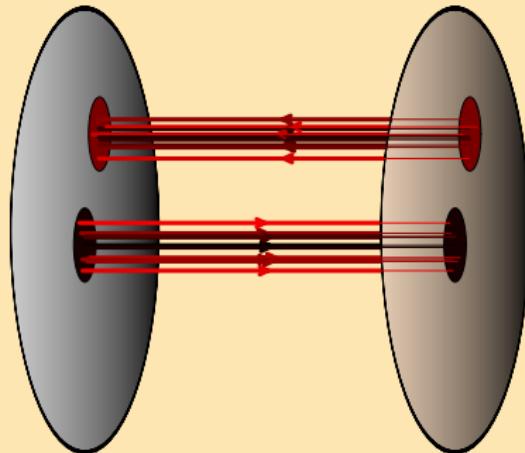
Glasma longitudinal correlations and the ridge

Initial glasma fields are longitudinal (▶ “flux tube”)



Glasma longitudinal correlations and the ridge

Initial glasma fields are longitudinal (▶ “flux tube”)

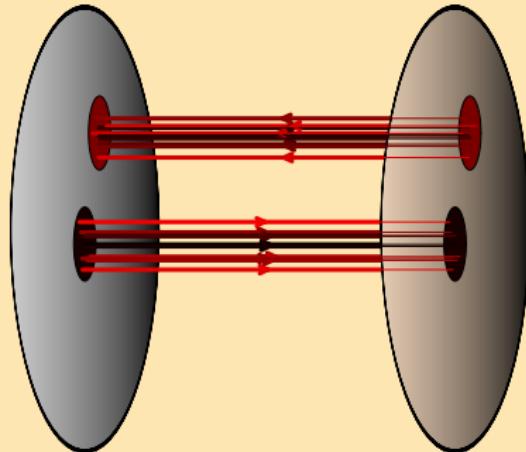


Essential for correlations

- ▶ Boost invariant (LO in α_s)
- ▶ Correlation length $1/Q_s$

Glasma longitudinal correlations and the ridge

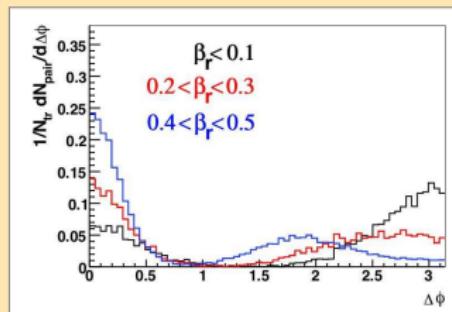
Initial glasma fields are longitudinal (▶ “flux tube”)



Essential for correlations

- ▶ Boost invariant (LO in α_s)
- ▶ Correlation length $1/Q_s$

Azimuthal structure from radial velocity + freezeout Voloshin
-03, Shuryak -07, Pruneau Gavin, Voloshin
-07



First to combine these two Dumitru, Gelis, McLerran, Venugopalan -08

Multiparticle correlations, power counting

Basic power counting: $\frac{dN}{d^3 p} \sim \frac{1}{\alpha_s}$

Fixed sources: correlations loop/quantum effects, suppressed by α_s

E.g. Poisson $\overbrace{\langle N^2 \rangle}^{1/\alpha_s^2 + \dots} - \overbrace{\langle N \rangle^2}^{1/\alpha_s^2 + \dots} = \overbrace{\langle N \rangle}^{1/\alpha_s + \dots}$

Multiparticle correlations, power counting

Basic power counting: $\frac{dN}{d^3 p} \sim \frac{1}{\alpha_s}$

Fixed sources: correlations loop/quantum effects, suppressed by α_s

E.g. Poisson $\overbrace{\langle N^2 \rangle}^{1/\alpha_s^2 + \dots} - \overbrace{\langle N \rangle^2}^{1/\alpha_s^2 + \dots} = \overbrace{\langle N \rangle}^{1/\alpha_s + \dots}$

But in CGC must average over sources:

$$\left\langle \frac{dN}{d^3 p_1} \cdots \frac{dN}{d^3 p_n} \right\rangle_{\text{conn.}} = \left[\int_{[\rho]} \underbrace{W[\rho_1(y)] W[\rho_2(y)]}_{\text{source}} \frac{dN}{d^3 p_1} \cdots \frac{dN}{d^3 p_n} \right]_{\text{conn.}} \sim \frac{1}{\alpha_s^n}$$

LLog corrections factorize into evolution of **source**.

E.g. neg. bin $\overbrace{\langle N^2 \rangle}^{1/\alpha_s^2} - \overbrace{\langle N \rangle^2}^{1/\alpha_s^2} = \frac{1}{k} \overbrace{\langle N \rangle^2}^{1/\alpha_s^2} + \overbrace{\langle N \rangle}^{1/\alpha_s}$

Multiparticle correlations, power counting

Basic power counting: $\frac{dN}{d^3 p} \sim \frac{1}{\alpha_s}$

Fixed sources: correlations loop/quantum effects, suppressed by α_s

E.g. Poisson $\overbrace{\langle N^2 \rangle}^{1/\alpha_s^2 + \dots} - \overbrace{\langle N \rangle^2}^{1/\alpha_s^2 + \dots} = \overbrace{\langle N \rangle}^{1/\alpha_s + \dots}$

But in CGC must average over sources:

$$\left\langle \frac{dN}{d^3 p_1} \cdots \frac{dN}{d^3 p_n} \right\rangle_{\text{conn.}} = \left[\int_{[\rho]} \underbrace{W[\rho_1(y)] W[\rho_2(y)]}_{\text{LLog corrections}} \frac{dN}{d^3 p_1} \cdots \frac{dN}{d^3 p_n} \right]_{\text{conn.}} \sim \frac{1}{\alpha_s^n}$$

LLog corrections factorize into evolution of **source**.

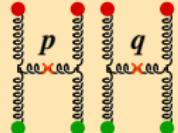
E.g. neg. bin $\overbrace{\langle N^2 \rangle}^{1/\alpha_s^2} - \overbrace{\langle N \rangle^2}^{1/\alpha_s^2} = \frac{1}{k} \overbrace{\langle N \rangle^2}^{1/\alpha_s^2} + \overbrace{\langle N \rangle}^{1/\alpha_s}$

Dominant correlations come from sources

i.e. enhanced by $\ln 1/x \sim 1/\alpha_s$

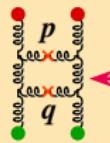
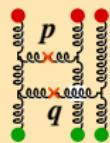
AA is simpler than pA!

Armesto, McLellan, Pajares -06



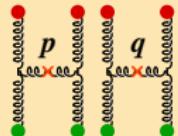
Correlations from

- ▶ Sources ("disconnected", "classical")
- ▶ Loops ("connected", "quantum")



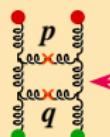
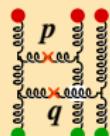
AA is simpler than pA!

Armesto, McLellan, Pajares -06



Correlations from

- ▶ Sources (“disconnected”, “classical”)
- ▶ Loops (“connected”, “quantum”)

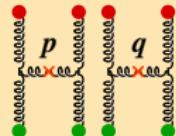


Power counting:

- ▶ “A”: $\rho \sim 1/g$
- ▶ “p”: $\rho \sim g$

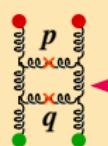
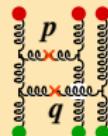
AA is simpler than pA!

Armesto, McLellan, Pajares -06



Correlations from

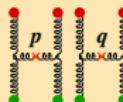
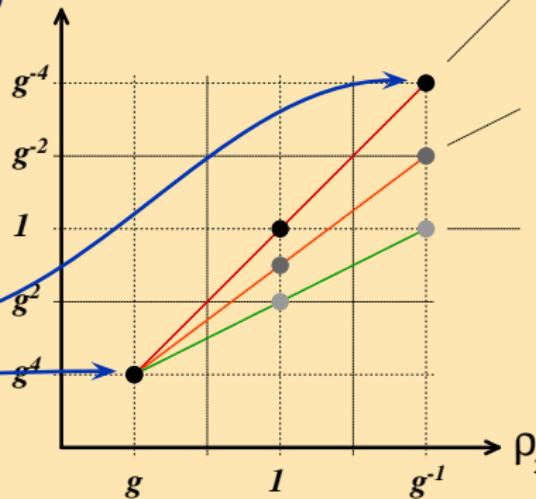
- ▶ Sources ("disconnected", "classical")
- ▶ Loops ("connected", "quantum")



- ▶ AA: sources only
- ▶ pA: both
- ▶ pp: gluons from same ladder

Power counting:

- ▶ "A": $\rho \sim 1/g$
- ▶ "p": $\rho \sim g$



Glittering Glasma

$$W[\rho] = \exp\left[-\int d^2\mathbf{x}_T \frac{\rho^a(\mathbf{x}_T)\rho^a(\mathbf{x}_T)}{g^4\mu^2}\right]$$

Correlations simple in MV model and dilute limit (small ρ)

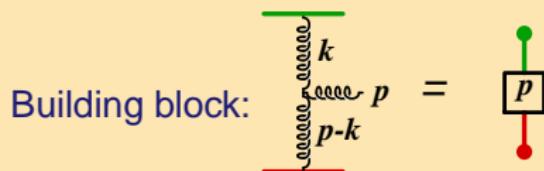
- ▶ 2-particle Dumitru, Gelis, McLerran, Venugopalan -08
- ▶ 3-particle Dusling, Fernandez-Fraile, Venugopalan -09
- ▶ n -particle Gelis, T.L., McLerran -09

Glittering Glasma

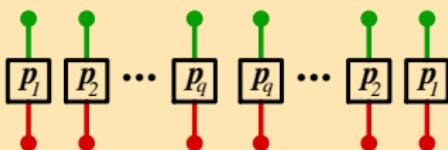
$$W[\rho] = \exp\left[-\int d^2\mathbf{x}_T \frac{\rho^a(\mathbf{x}_T)\rho^a(\mathbf{x}_T)}{g^4\mu^2}\right]$$

Correlations simple in MV model and dilute limit (small ρ)

- ▶ 2-particle Dumitru, Gelis, McLerran, Venugopalan -08
- ▶ 3-particle Dusling, Fernandez-Fraile, Venugopalan -09
- ▶ n -particle Gelis, T.L., McLerran -09



Connect dots in



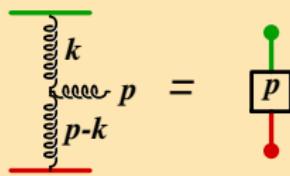
Glittering Glasma

$$W[\rho] = \exp\left[-\int d^2\mathbf{x}_T \frac{\rho^a(\mathbf{x}_T)\rho^a(\mathbf{x}_T)}{g^4\mu^2}\right]$$

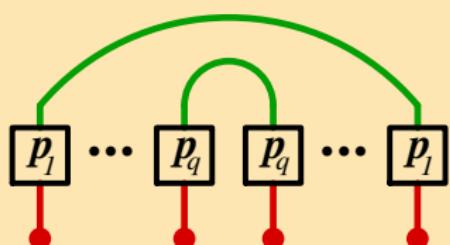
Correlations simple in MV model and dilute limit (small ρ)

- ▶ 2-particle Dumitru, Gelis, McLerran, Venugopalan -08
- ▶ 3-particle Dusling, Fernandez-Fraile, Venugopalan -09
- ▶ n -particle Gelis, T.L., McLerran -09

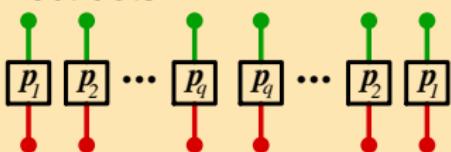
Building block:



Dominant contributions



Connect dots in



Result

Number of diagrams $\sim (q-1)!$

Negative binomial

Moment $m_q \equiv \langle N^q \rangle - \text{disc.}$

$$m_q = (q-1)! k \left(\frac{\bar{n}}{k} \right)^q$$

$$k \approx \frac{(N_c^2 - 1) Q_s^2 S_\perp}{2\pi}$$

$$\bar{n} = f_N \frac{1}{\alpha_s} Q_s^2 S_\perp$$

Negative binomial

Moment $m_q \equiv \langle N^q \rangle - \text{disc.}$

$$m_q = (q-1)! k \left(\frac{\bar{n}}{k} \right)^q$$

$$k \approx \frac{(N_c^2 - 1) Q_s^2 S_\perp}{2\pi}$$

$$\bar{n} = f_N \frac{1}{\alpha_s} Q_s^2 S_\perp$$

This is a neg. bin.

- ▶ Old exp. observation
- ▶ Note $k \sim \sqrt{s}^\lambda$

Negative binomial

Moment $m_q \equiv \langle N^q \rangle - \text{disc.}$

$$m_q = (q-1)! k \left(\frac{\bar{n}}{k} \right)^q$$

$$k \approx \frac{(N_c^2 - 1) Q_s^2 S_\perp}{2\pi}$$

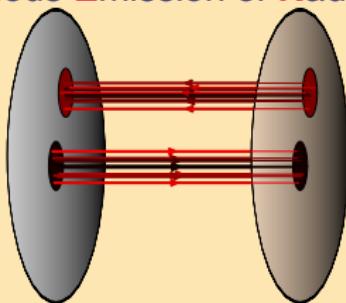
$$\bar{n} = f_N \frac{1}{\alpha_s} Q_s^2 S_\perp$$

This is a neg. bin.

- ▶ Old exp. observation
- ▶ Note $k \sim \sqrt{s}^\lambda$

(Negative binomial is sum of k independent BE's)

GLuon Intensification Through
Tenacious Emission of Radiation.



$Q_s^2 S_\perp = N_{FT}$, # of flux tubes

$k \approx N_{FT}(N_c^2 - 1)$ = emitters

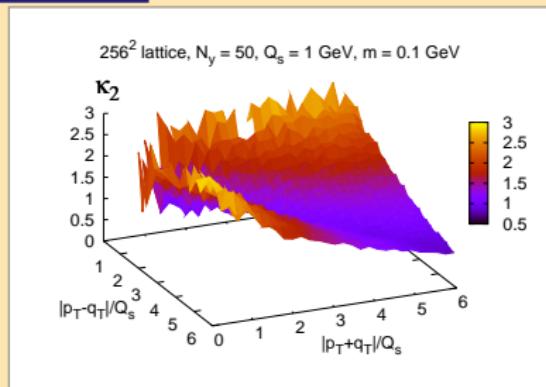
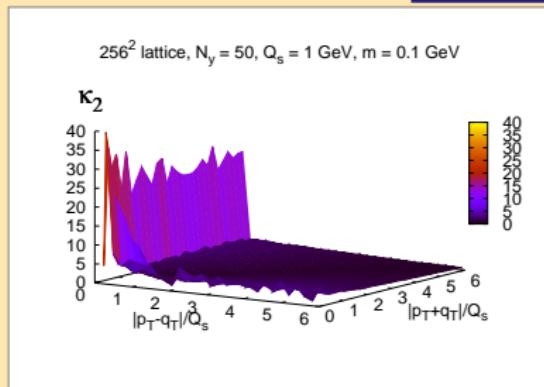
Each emitter produces particles with Bose-Einstein distribution

Boost invariant correlation: full numerical calculation

T.L., Srednyak, Venugopalan, -09

$$\kappa_2(\mathbf{p}_T, \mathbf{q}_T) = \overbrace{S_{\perp} Q_s^2}^{\# \text{ of independent regions}} \times \frac{\left\langle \frac{d^2 N_2}{dy_p d^2 \mathbf{p}_T dy_q d^2 \mathbf{q}_T} \right\rangle}{\left\langle \frac{dN}{dy_p d^2 \mathbf{p}_T} \right\rangle \left\langle \frac{dN}{dy_q d^2 \mathbf{q}_T} \right\rangle} - 1$$

Dilute limit: $\kappa_2(\mathbf{p}_T, \mathbf{q}_T) \sim 1/(N_c^2 - 1)$ constant up to logs.

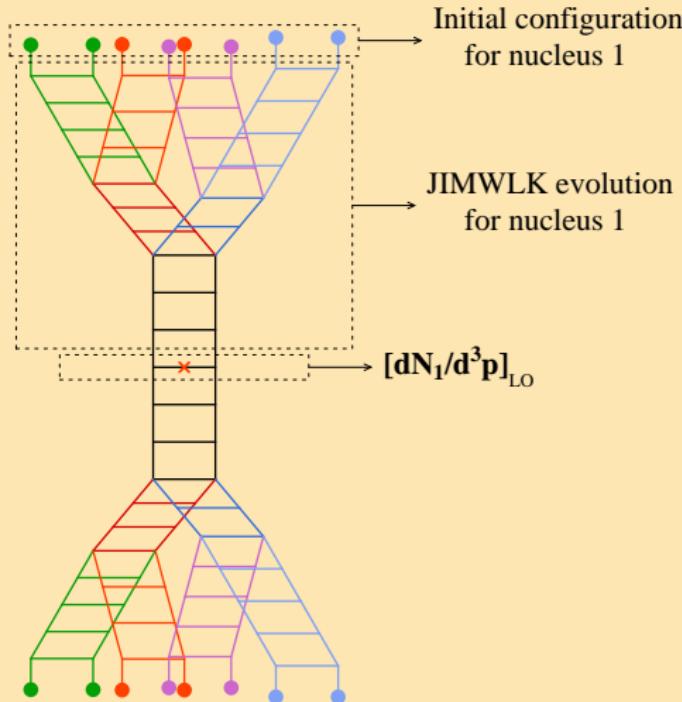


Ridge estimate: $\kappa_2 \approx 1 \dots 1.5$
(Note: different momenta)

Multiplicity distribution: $\kappa_2 \approx 4$

Unequal rapidities

Gelis, T.L., Venugopalan -08

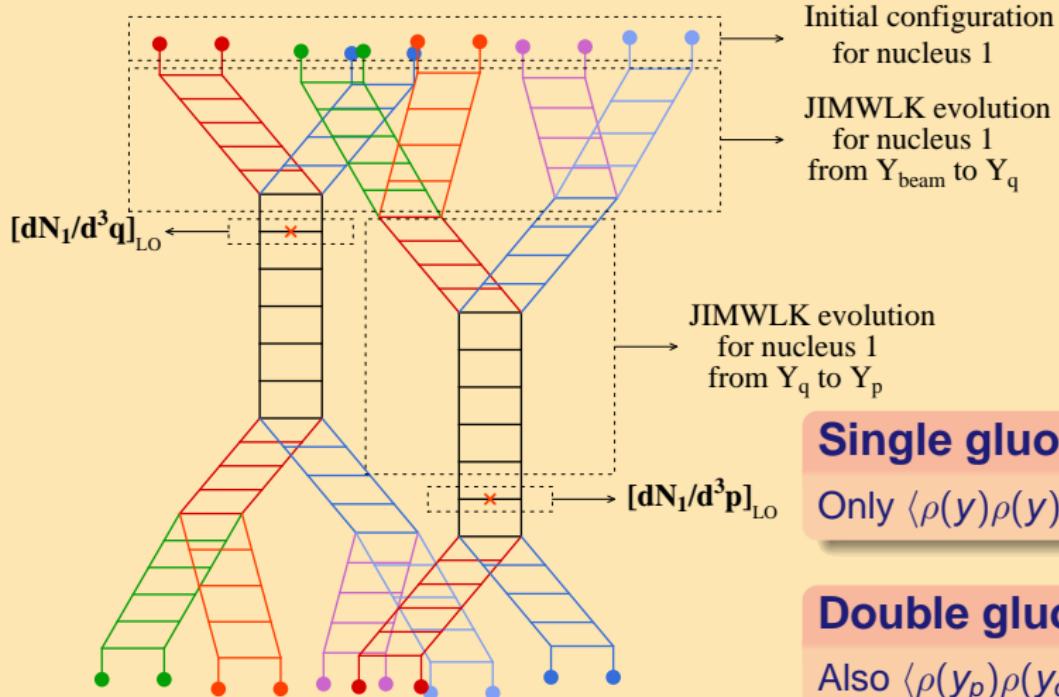


Single gluon

Only $\langle \rho(y)\rho(y) \rangle$

Unequal rapidities

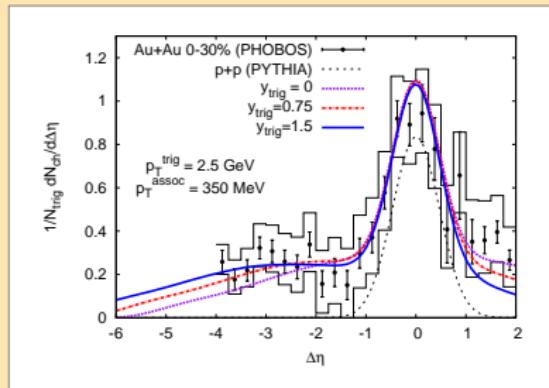
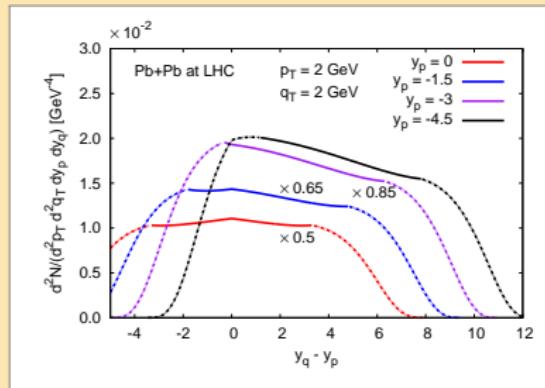
Gelis, T.L., Venugopalan -08



First calculation of rapidity dependence

k_T -factorized approximation Dusling, Gelis, T.L., Venugopalan, -09

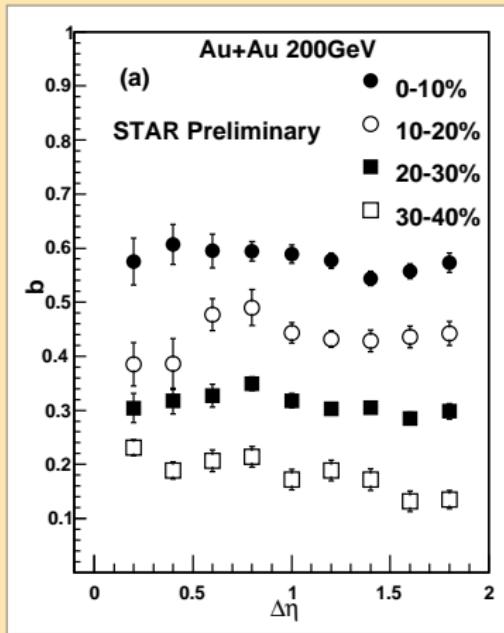
$$C(\mathbf{p}, \mathbf{q}) \sim \int_{\mathbf{k}_T} \left\{ \overbrace{\Phi_{A_1}^2(y_p, \mathbf{k}_T) \Phi_{A_2}(y_p, \mathbf{p}_T - \mathbf{k}_T)}^{3 \text{ at } y_p} \overbrace{\Phi_{A_2}(y_q, \mathbf{q}_T + \mathbf{k}_T)}^{1 \text{ at } y_q} \right. \\ \left. + (\mathbf{k}_T \leftrightarrow -\mathbf{k}_T) + (A_1 \leftrightarrow A_2) \right\}$$



STAR Forward-Backward correlation data

$$b = \frac{\langle N_F N_B \rangle - \langle N_F \rangle \langle N_B \rangle}{\langle N_F^2 \rangle - \langle N_F \rangle^2}$$

Huge increase in correlation, but what is actually measured?



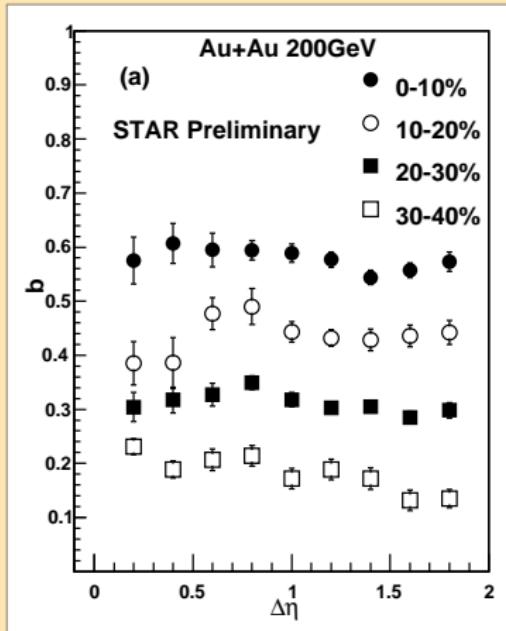
STAR Forward-Backward correlation data

$$b = \frac{\langle N_F N_B \rangle_{N_R} - \langle N_F \rangle_{N_R} \langle N_B \rangle_{N_R}}{\langle N_F^2 \rangle_{N_R} - \langle N_F \rangle_{N_R}^2}$$

at fixed N_R

Huge increase in correlation, but what is actually measured?

STAR, B. I. Abelev et al., Phys. Rev. Lett 103, 172301 (2009):



In order to eliminate (or at least reduce) the effect of impact parameter (centrality) fluctuations on the measurement of the FB correlation strength, each relevant quantity (N_f , N_b , N_f^2 , $N_f N_b$) was obtained on an event-by-event basis as a function of the event multiplicity, N_R . The average uncorrected mean multiplicities ($\langle N_f \rangle_{uncorr}$, $\langle N_b \rangle_{uncorr}$, $\langle N_f^2 \rangle_{uncorr}$, and $\langle N_f N_b \rangle_{uncorr}$) in each centrality bin were calculated from a fit to the N_{ch} dependences [19, 20]. The functional forms that were used are linear in N_f , N_b and quadratic in N_f^2 and $N_f N_b$ for all $\Delta\eta$ bins. Tracking efficiency and acceptance corrections were then applied to $\langle N_f \rangle_{uncorr}$, $\langle N_b \rangle_{uncorr}$, $\langle N_f^2 \rangle_{uncorr}$, and $\langle N_f N_b \rangle_{uncorr}$ to each event. Then the corrected values of $\langle N_f \rangle$, $\langle N_b \rangle$, $\langle N_f^2 \rangle$, and $\langle N_f N_b \rangle$ for each event were used to calculate the backward-forward and forward-backward dispersions, D_{bf}^2 and D_{ff}^2 , binned by centrality, and normalized by the total number of events in each bin. This method removes the dependence of the FB correlation strength on the width of the centrality bin. As

“...($N_F, N_B, N_F^2, N_F N_B$) was obtained on an event-by-event basis as a function of the event multiplicity [N_R] ...”

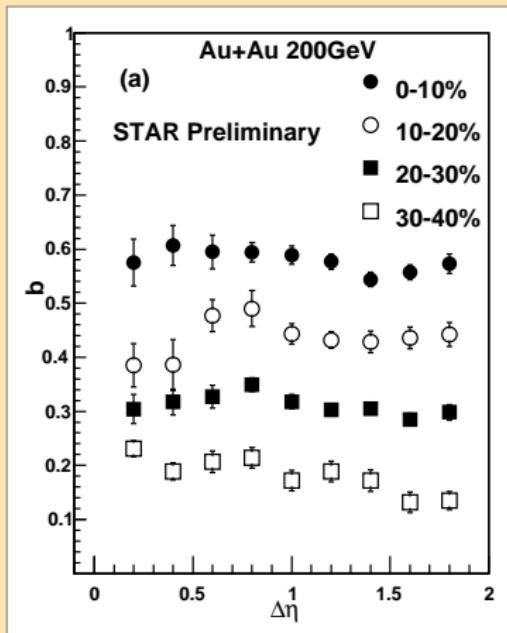
STAR Forward-Backward correlation data

$$b = \frac{\langle N_F N_B \rangle_{N_R} - \langle N_F \rangle_{N_R} \langle N_B \rangle_{N_R}}{\langle N_F^2 \rangle_{N_R} - \langle N_F \rangle_{N_R}^2}$$

at fixed N_R

Huge increase in correlation, but what is actually measured?

STAR, B. I. Abelev et al., Phys. Rev. Lett 103, 172301 (2009):



3-particle correlation:
 N_F , N_B and N_R

“... $(N_F, N_B, N_F^2, N_F N_B)$ was obtained on an event-by-event basis as a function of the event multiplicity [N_R] ...”

Simple parametrization with long range correlation

Parametrize correlations:

$$C(\eta, \eta')|_{N_{\text{part}}} = \delta(\eta - \eta') \left\langle \frac{dN}{d\eta} \right\rangle + \left[K + \alpha \theta(Y - |\eta - \eta'|) \right] \left\langle \frac{dN}{d\eta} \right\rangle \left\langle \frac{dN}{d\eta'} \right\rangle,$$

- ▶ Local (Poisson)
- ▶ Long range piece
- ▶ Short range correlation

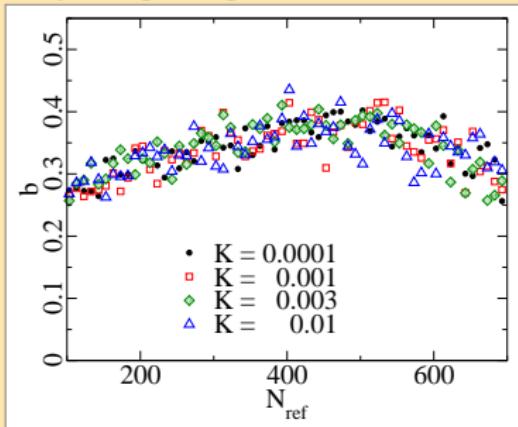
$$\begin{aligned} F &= [0.8, 1.0] \\ B &= [-1.0, -0.8] \\ R &= [-0.5, 0.5] \end{aligned}$$

Construct MC Glauber event:

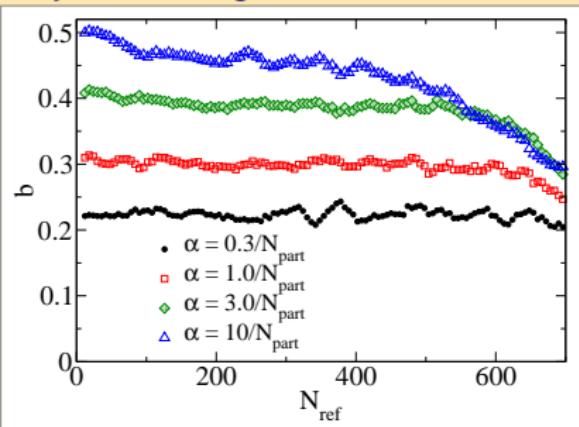
1. Fluctuating N_{part} ,
2. multiplicities $N_F, N_B, N_R \sim N_{\text{part}}$ with this correlation
3. calculate $b = \text{correlation between } N_F \text{ and } N_B \text{ for fixed } N_R$

Result from parametrization

Fixed short range $\alpha = 0.01$,
vary long range K



Fixed long range $K = 1/N_{\text{part}}$,
vary short range α



Result for b

- independent of long range correlation
- below 0.5 for any reasonable values;
- mostly depends on short range (α), i.e. fluctuations

Conclusions

- ▶ Gluon correlations qualitatively different in strong field/weak coupling regime
- ▶ CGC & Glasma naturally produces a negative binomial multiplicity distribution for gluons.
- ▶ STAR F-B multiplicity correlations \implies strong long range rapidity correlations in central AA
 - ▶ exp observable actually 3-particle correlation, not a 2-particle one;

Backups

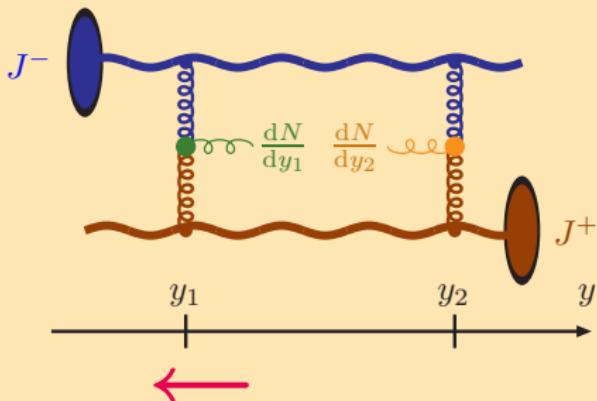
Source correlations at unequal rapidities

Diffusion analogy: $\langle x(t)x(t') \rangle = 2D \min(t, t')$

Evolution direction of leftr mover.



$$\langle J_1^- J_2^- \rangle = \underbrace{\langle J_1^- J_1^- \rangle}_{\text{Earliest rapidity in evolution}}$$



Evolution direction of rightmover

$$\langle J_1^+ J_2^+ \rangle = \overbrace{\langle J_2^+ J_2^+ \rangle}^{\text{Earliest rapidity in evolution}}$$